Magnetism in Growth

THE LIBRARY OF THE
JUN 2 - 1939
UNIVERSITY OF ILLINOIS

BEING THE

EIGHTH ROBERT BOYLE LECTURE

DELIVERED BEFORE THE

OXFORD UNIVERSITY JUNIOR SCIENTIFIC CLUB

On June 6, 1901

BY

SILVANUS P. THOMPSON, B.A., D.Sc., F.R.S.

PRINCIPAL OF AND PROFESSOR OF PHYSICS IN THE CITY AND GUILDS' TECHNICAL COLLEGE, FINSBURY

LONDON: HENRY FROWDE, AMEN CORNER, E.C.
EDINBURGH: 12 FREDERICK STREET. GLASGOW: 104 WEST GEORGE STREET
OXFORD: 116 HIGH STREET

1902

Digitized by Google

OXFORD
HORACE HART, PRINTER TO THE UNIVERSITY

Digitized by Google

504
Ox2r
no. 8

Magnetism in Growth

'THOUGH the vertues of the *Loadstone* be none of the least famous of *Occult* Qualities, and are perhaps the most justly admired; yet I shall venture to offer something to make it probable, that some, even of these, may be introduced into bodies by the production of *Mechanical* changes in them.' So wrote Robert Boyle in 1676 in the Tract, published by Davis of Oxford, entitled *Experiments and Notes about the Mechanical Production of Magnetism.* In the two centuries and a quarter which have elapsed since he wrote, marvellous progress has been made in our knowledge of magnetism. But marvellous as that progress is, both in its theoretical and its technical aspects, it yet remains to be true that those occult qualities of magnetism which then, and for centuries before, had excited the admiration of mankind are still *occult*, not in the sense only that they need to be investigated by experiment, but that their ultimate cause still remains unexplained, though none need so despair of science as to declare them unexplainable. Boyle, whose illuminating genius wandered over the whole range of the physical sciences, himself contributed, in the Tract already quoted, to the unravelling of the mysteries of the magnet; and the

Digitized by Google

most recent of experimental researches into those magnetic properties, which he quaintly described as 'the vertues of the Loadstone' have amply justified the suggestion that 'some even of these [occult qualities] may be introduced into bodies by the production of mechanical changes in them.'

What then is the process of magnetization, by which these same virtues or qualities are introduced into a body? In what does the communication of magnetism to a piece of iron consist? What are the bodies which are susceptible of being magnetized? How is that reception of magnetism related to the production of mechanical changes in them? In a word, when the magnetic properties are imparted to a piece of iron, and it becomes a magnet, how does its magnetism grow? That is the problem to which your attention is to be directed in the hour devoted to the pious memory of Robert Boyle.

Of the process of magnetization of iron there are two chief varieties which may be briefly described as the old and the new. The old process, which is prehistoric, consists in stroking or touching the piece of iron which is to be magnetized, with some pre-existing magnet. The new, invented early in the last century, consists in surrounding the piece of iron with a conducting coil of copper wire, by means of which an electric current from a battery or other suitable source is caused to circulate around it, when at once it becomes magnetized. In either case the question arises: how, during the process of magnetization, does the magnetism of the iron grow?

Again, if we range over the whole array of material substances known to the chemist, in order to ascertain

Digitized by Google

which of them are magnetic, we find that there are but three—the metals iron, nickel, and cobalt—together with their alloys and a few compounds containing them, which are susceptible of receiving to any appreciable or practical degree the property which we call magnetism. The *primâ facie* tests which we acknowledge, by the way, to tell whether a body possesses magnetism or not, are two in number: it shall be capable of attracting pieces of iron; and if properly suspended or pivotted, it will of itself turn and point north and south. There are, of course, other tests. It shall show, on examination, magnetic poles, of opposite kinds, capable of exercising the familiar attractions and repulsions with the poles of other magnets. Or in the infrequent case of the iron ring forming a closed magnetic circuit destitute of any polar ends, there are laboratory tests which need not be here considered. As we consider this fact that no substances are magnetic except those which consist of or contain iron, cobalt, or nickel, the question forces itself upon us: why only these? Why should these elements alone be susceptible of acquiring that occult quality called the magnetic state, while copper, manganese, tin, and silver and the other metals are not susceptible? To investigate any occult quality it is necessary to try experiments so as to ascertain the facts upon which to base an intelligent generalization. We must endeavour in the case of this occult quality of magnetism to ascertain its physical, or, as Robert Boyle would have said, its mechanical relations.

Amongst the facts of magnetization of iron there is one which was known to and remarked upon by Robert Boyle, and by Dr. William Gilbert, seventy years before; namely a case of apparently spontaneous

Digitized by Google

acquisition of magnetism by an iron rod. The circumstance was observed in 1586 by a certain Julius Caesar Moderatus, surgeon and apothecary of Rimini [1], that an iron rod which had supported an ornament on the top of the pinnacle of the campanile of the Augustinian church at Rimini, and which had remained for ten years bent by the wind, was found, when removed for repair, to have become a magnet, and to be capable of attracting other pieces of iron. There was much marvel how a metal rod standing in the air, and neither buried in the soil nor submerged under water, could have been—as they considered—changed into loadstone. Pieces of this spontaneous magnet were kept as curiosities, one being given to Filippo Costa, an apothecary of

[1] See the following passage from a tract published in 1586 in Mantua, entitled: *Lettera dell' excell^mo. Cavallara all' excellentissimo Signor Girolamo Conforto* :—

'E poi nella nostra Città di Mantoua M. Filippo Costa Cittadino commodo de' beni di Fortuna ma più comodo de' beni dell' animo. Perche per essercitio della Città fa caminare una principalissima Specieria dirizzata da gli avoli suoi sotto l'insegna del Rè; & poi per particolar diletto, & in gratia de gli intendenti mantiene, & arrichisce tuttavia un suo Studioliuo, anzi gentile Theatro di quei più rari semplici, che all' età nostra siano scoperti. Questi con mia molta maraviglia tra l'altre cose rare mi ha fatto vedere un pezzo di Ferro si fattamẽte tramutato in Calamita, o Magnete, che egli à se tira il ferro al paro di qual si voglia valorosa Calamita. Et il ritrovamento di questo ferro è stato tale. In Arimini era il Campanile della Chiesa di S. Agostino con una Piramide nel sommo, nella quale era un grosso baston di ferro, che sosteneva un ornamento di mattoni fatto a modo di ghianda. Venne un vento violentissimo, & piegò quel ferro, il quale stete così per dieci anni, dopo i quali quei Religiosi volendo riformar quell' ornamento, diedero quel ferro ad un Fabro, che lo dirizzasse. Questo ferro, veduto da M. Giulio Cesare Moderato Chirurgo, & parutogli simile alla Calamita, & con l'esperienza trovatolo tirar l'altro ferro, fu spezzato, & datine alcuni frammenti a M. Francesco Acoromboni Spetiale diligẽtissimo in Arimini, & da lui al Costa nostro una parte ne fu mandata. Intorno a questo ferro mi si porge maraviglia, come egli sia passato in pietra tale, & poi stando in aria, & non sotto terra, o sotto l'acque, come sogliono gli altri petrificati.'

Digitized by Google

Mantua. Another piece was preserved for over sixty years, being described among the rarities of the *Musaeum Metallicum* of Ulysses Aldrovandus of Bologna, in 1648. Robert Boyle refers to this tale, in those *Notes and Experiments about the Mechanical Production of Magnetism* to which allusion has been made. True to his instincts as a 'sceptical Chymist,' he questioned the allegation that the metal had been turned into stone, though he accepted the fact of the acquisition of magnetism without demur. As a matter of fact this spontaneous occurrence of magnetism in elevated iron rods does not stand alone; Dr. Martin Lister mentions, in his *Journey to Paris*, in 1699, another magnetic iron bar taken from the steeple of the cathedral of Chartres. The narrative of Caesar Moderatus is also commented upon by Gilbert in his *De Magnete*, and by Sir Thomas Browne in the *Pseudodoxia Epidemica*. Gilbert was indeed so struck by it that he set to work to investigate by experiment the possibility of communicating the magnetic virtue to iron by mechanical means. In this he was entirely successful. His book, published in 1600, describes amidst many new and ingenious experiments two new modes of communicating magnetism to iron. Both of them depend upon the inductive influence of the earth's own magnetism, which he himself did so much to elucidate. In the first of these methods the iron rod must be laid on an anvil so as to point in the north-south direction, and while in this position must be hammered. The crude woodcut (here reproduced on a diminished scale) represents the smith in the act of smiting the iron. This cut (Fig. 1) has a curious history. It is copied from an etching in a rare book

Digitized by Google

of Fables by one Cornelius Kiliani, published at Cologne in 1594; and the engraver has added the words *Septentrio* and *Auster* at the sides to indicate the position of the iron. Gilbert's second process consisted in heating the iron red-hot and letting it cool while lying in the north-south position. He found also that lumps of iron ore, and even of red clay, when

FIG. 1.

so treated acquired a feeble magnetic polarity. Again the question arises for our consideration, what is it that happens, during these processes, to the iron to cause it to become magnetic: or, how does its magnetism grow? Robert Boyle's subsequent repetition of the experiment of percussion, in which he found that magnetism was imparted to an iron rod by hitting it while it was vertical, or even by merely letting it stand vertically for some

Digitized by Google

time, did not help much to answer the question. Even in Gilbert's time it was known that the harder kinds of iron retain their magnetism better (and therefore endure the shocks of rough usage longer) than the soft sorts. Archdeacon Barlowe, in 1616, told the world the secret of making good compass-needles. They were to be fashioned from blade-steel or edge-iron; then hardened by making bright red-hot, and quenching suddenly in water so as to be 'as brickle as glass,' then tempered blue by reheating over a piece of red-hot iron: finally stroked with the loadstone. Servington Savery in 1729 fully reinvestigated the matter, and demonstrated the superior retentivity of hard steel. For two centuries after Gilbert's time no new fact of importance in magnetism was discovered. The practical advantage of making steel magnets of the horse-shoe shape with the poles set very close together was first made known by Geuns of Venlo, in 1768.

But in 1820 came the discovery of Oersted that a magnetic needle can be deflected by passing an electric current through a wire above it; a discovery followed by the experiments of Arago, who showed that steel needles could be magnetized by merely poking them into the interior of a hollow tube of glass or brass around which an electric current was circulating in a copper wire coiled upon the tube. In 1825 came William Sturgeon's invention of the soft iron electro-magnet. You take a piece of soft wrought iron—it may be bent to a horse-shoe, or may be straight,—wind upon it a coil of copper wire, carefully insulating the copper so that it shall nowhere touch the iron core. Then, so soon as you cause an electric current to flow through the wire so that it circulates around the iron core, that

Digitized by Google

iron core becomes a powerful magnet. As soon as the electric current is stopped the magnetism of the iron core also disappears. Here for the first time in history was a magnet the powers of which were under command. You 'make' the electric circuit by pressing a button; at once the magnetism is evoked, and the magnet pulls obediently. You 'break' the circuit by releasing the button; the current ceases, and the magnet instantly drops its load. Here you have the magnet under control—under control, in fact, from a place that may be far away. Of all the marvels of the magnet surely this is the most surprising. Not the circumstance that you can manipulate it from a place miles away: that is obvious enough if your copper wire circuit extends (on telegraph poles, or submerged in a cable) across the intervening space. No, the real marvel is the production of magnetism in the iron core when you do absolutely nothing to it. The electric current never enters it: the flow of the electricity is confined to the copper wire, merely circulating round and round outside the core. We shall have occasion to consider this further. Meantime I will again remark that the question inevitably suggests itself, what is it that happens in the iron while the circulation of electric current around outside it is in progress? In other words;—how does the magnetism grow?

A few years after this momentous discovery an American, Page, made the curious observation, that the iron core, in the act of thus acquiring or in the act of losing its magnetic quality, when the electric current is turned on, or turned off, emits a faint sound, a metallic clink, as though some one had lightly tapped the end of the iron core. Now a sound emitted from a solid

Digitized by Google

body implies a state of vibration in that body. Vibration is a mechanical fact which can be mechanically investigated. That was indeed done by the late Dr. Joule, who showed that in the act of magnetization the iron rod grew a little longer by a minute fraction of its own length; and again returned to its original length when it ceased to be magnetic. He also found that the volume of the iron did not alter, the increase in length being accompanied by a corresponding diminution in cross-section. Subsequently Barrett found nickel to contract during magnetization. The phenomena, which are complicated, have been fully investigated by Bidwell, Tomlinson and others. This singular mechanical behaviour of iron during the act of magnetization is most significant; but as yet it gives no answer to the question, how does the magnetism grow?

Another line of investigation is afforded by a study of the quantitative relations between the amount of the magnetizing force (as determined by the amount of circulation of the surrounding current) and the amount of magnetization that results. Are they proportional one to the other? If one doubles the circulation of current will the iron core become magnetized twice as strongly? The early experimenters may have thought so, but Joule found by trying that any such proportionality came to a rude end. The iron appeared to be unable to acquire more than a certain amount of inherent magnetization: it acquired a state of practical, though not an absolutely complete saturation. Fuller investigation came at the hands of Weber, of Rowland, of Bosanquet, of Chwolson, of Siemens, of Ewing, and of Hopkinson. It appeared that when a specimen of iron was subjected to magnetizing forces which were gradu-

Digitized by Google

ally caused to increase (by turning on more and more electric current), the resulting magnetization went through three stages. At first, when the exciting forces were weak, the magnetization acquired was also weak and nearly proportional to those forces. Then, when the exciting forces had attained a certain value, a further increase in them caused a sudden increase in the amount of the magnetization, the iron passing abruptly from a very slightly to a very highly magnetized state. This

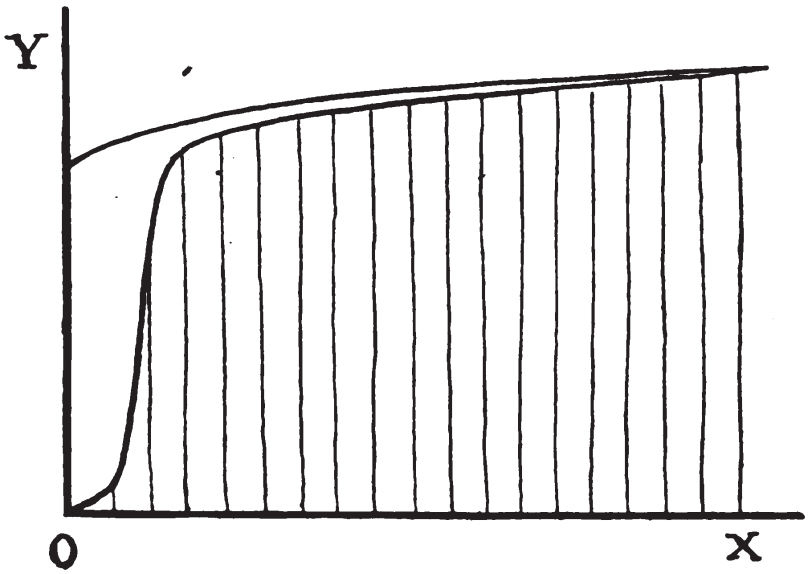

FIG. 2.

is graphically plotted in Fig. 2. Then came a third stage, in which any further increase in the exciting forces produced a comparatively small increase in the magnetization, the iron being practically saturated. In the case of hard steel the three stages ran into one another, the second stage being much less sudden; and much greater magnetizing forces were required to bring the material up to the same high degree of magnetization. On reducing the magnetizing forces back to zero there always remained some residual magnetization;

Digitized by Google

but in the case of soft iron this was held very unstably. By applying a reversed magnetizing force of gradually increasing amount it was possible to measure the fixity of the residual magnetization, which would disappear almost as abruptly as it had originally grown. All these facts, gathered with laborious patience, began to throw some light on the process of magnetization. But why these three stages? Why this almost abrupt transition in the second stage from feeble to nearly full magnetization?

For long the nature of the quality called magnetism had been a matter of speculation. Dr. Gilbert, finding that whenever a magnet was broken into two parts, each part was a complete magnet with north and south poles, compared it to a piece of twig, each portion of which, if cut in two, has still a top and a bottom end. Gilbert's notions were far more sensible than those prevalent in the eighteenth century, which ascribed magnetic actions to the existence of certain alleged magnetic 'fluids.' This nonsense, which only became even tolerable as a hypothesis when Poisson proposed to ascribe these fluids to the molecules of the iron and not to the magnets themselves, all disappeared with fuller knowledge. Ampère had made the brilliant speculation that possibly all magnetism might consist in the perpetual circulation of electric currents within the magnet: the main difficulty of the speculation was to account for such circulation being perpetual.

If each portion of a magnet is itself a magnet, it will obviously be of some interest to study the magnetic behaviour of such materials as powdered loadstone and filings of iron or steel. The magnetic behaviour of iron filings has indeed been studied since the days when

Digitized by Google

Giambattista della Porta (author of the *Magia Naturalis*, published at Naples in 1561) described the experiment of sprinkling iron filings over a piece of card below which two magnets were moved about; the filings standing up in serried tufts and advancing or retreating like two armies manœuvring. You are all familiar with the patterns of magnetic lines which can be obtained by sprinkling iron filings thus above a magnet—patterns which reveal the directions of the magnetic forces in the surrounding space, and which Faraday showed to have such wonderful significance.

There are, however, two experiments with filings to which your attention is invited. If you take a glass tube, loosely filled with iron filings, and set to work to magnetize it by either the old method of stroking with magnets, or by the modern method of surrounding it with a circulation of electric current, you will find that it is quite easy to make it into a magnet. The filing-tube will be found, by putting it near a compass-needle to test it, to be a magnet with a north-pole at one end and a south-pole at the other. If you examine it you will observe that the filings inside the tube are now arranged in more or less regular lines or chains, constituting a species of coarse structure from end to end. But, shake up the tube, and this acquired structure at once vanishes; and it will be found that the magnetization has also vanished. This is a most suggestive experiment, and a very easy one.

The other filing experiment is one which I found out about the year 1875. If you make some of the patterns of magnetic figures by sprinkling iron filings upon cardboard over a magnet, you can, as is well known, fix them permanently upon the cardboard by means of gum or

Digitized by Google

varnish. Now if the filing figures, so fixed, are removed and tested by their effect on a compass-needle, it will be observed that they are themselves permanently magnetic. Each figure is a magnet possessing poles, and its polarity is complementary to that of the magnet from which it was made. The spot where the north-pole of the magnet lay acts as a south-pole, and that where the south-pole lay acts as a north-pole. If you balance the piece of cardboard upon a pivot it will turn round and point in the north and south direction; the filings fixed in their magnetic pattern upon the card act as a magnet—nay more, *are* a magnet.

Reflection upon the known facts about the magnetic behaviour of iron filings afforded further clues to the nature of the operation called magnetization. It clearly had something to do with the arrangement of particles, with the minute structure of the bodies which can become magnets. Whatever might have been the brilliance of Ampère's speculation about the circulation of currents, it did not seem to be very closely tied to the observed facts.

Weber certainly drew less upon scientific credulity when he propounded the theory that every molecule of iron was a minute magnet; that so long as iron was in its ordinary non-magnetized state these minute molecular magnets were not arranged in any order, but all jumbled together in a miscellaneous way; that the act of magnetization consisted in turning these magnetic molecules round to point in one direction; and that there were internal resisting forces resembling friction which opposed the turning of the molecules. This molecular theory accounted very well for the facts up to a certain point. It afforded rational grounds for the existence of

Digitized by Google

a practical maximum of magnetic saturation; but it rendered no explanation of the three stages, nor of certain of the residual phenomena. Professor Ewing has propounded a molecular theory which does, however, account for these observed facts. Admitting the fundamental points of Weber's molecular theory, Ewing makes the supposition that the force which acts within the magnet opposing the turning of the molecules is not of the nature of friction, but is due to the mutual magnetic forces between the molecules themselves. To elucidate the matter he proceeded to construct a model. The whole thing is before you, arranged for projection upon the screen. A number of small pivotted compass-needles are arranged upon a glass sheet, at the sides of which are fixed coils of copper wire by which to produce a magnetizing force at will. At first, as will be noticed by looking at the configuration of the little magnets on the screen, they point in all sorts of directions, miscellaneously; but nevertheless one can trace out groupings which the magnets assume under mutual action. Or one can study the groupings separately by trying the experiments with a few magnets at one time, as with a group of four only, or with a group of seven only. It is then found that some configurations are stable, and others unstable. So long as there is no external magnetizing field to control the pointing of the magnets, it will be seen that no configuration is stable in which all the magnets point in one general direction: for if several of them point, say, to the right, then these that point to the right tend to influence the others to point to the left. If now the group of little magnets is subjected to the influence of a gradually-increased magnetizing force, the behaviour of the individual magnets

Digitized by Google

may be watched. The gradually increasing magnetizing force is obtained by placing near the group, at its sides, a pair of rather large magnetizing-coils of copper wire into which an electric current is introduced, the current being itself regulated by a suitable rheostat. When a weak but gradually increasing magnetic force is thus applied to any given group of magnets, it is observed that some of them begin to turn very slightly; but as the magnetizing force is increased there suddenly comes a point when some one (or more) of the magnets suddenly swings round, its position having become unstable. As it swings round, and oscillates around a new position, the other needles in its neighbourhood are affected. Usually a number of the others also swing round at the same time or just after, with the result that now all (or most) of the little magnets have assumed a general direction in obedience to the influence of the magnetizing force, though their mutual influences still affect them slightly and prevent them from pointing precisely parallel to the field. After this stage is attained, all that any further increase in the magnetizing force can effect is to make their pointing a little more precise. To bring them into absolute alignment would require an indefinitely great increase in the magnetizing force. The model, then, reproduces with surprising fidelity the three stages recognizable in the act of magnetization—the slight but proportional magnetization in the weak field: the sudden transition in the second stage from the state of miscellaneous arrangement to one of nearly complete alignment; and then the final small completion of alignment by the application of a very disproportionate increase in the directing forces. The facts about the retention of magnetism, the residual

Digitized by Google

effect left when the magnetizing force is removed, even the action of mechanical disturbance in lessening the amount of effect that remains, are all most admirably imitated in this model. No one can study its action through a series of operations without being convinced that it corresponds to the facts which it was designed to explain. Ewing's theory of magnetism is in fact Ewing's model.

Here it will be appropriate to introduce an experiment, due I believe to the late Sir William Grove, which I have often shown during the past twenty years, but which I am told is quite unknown in Oxford. It illustrates optically the circumstance that the act of magnetization, if applied to a mass of magnetic particles, brings them into alignment, and confers upon a mass of them a quasi-structure. The experiment consists in magnetizing a liquid in which magnetic particles are held in suspension—in short, a sort of magnetic mud. This mud is simply finely-divided magnetic oxide of iron suspended in water or glycerine. The oxide is prepared by taking an ordinary solution of ferrous sulphate, and converting two-thirds of the solution to a ferric salt by boiling with nitric acid. The excess of acid is neutralized, the ferrous and ferric solutions are mixed together again, and then precipitated by the addition of caustic alkali. A small quantity of this black magnetic powder in suspension will presently be poured into a short vertical glass tube surrounded by a magnetizing coil of wire. To observe the optical properties of this liquid, arrangements are made to throw a beam of light from the lantern vertically upwards through the tube, which has a flat bottom of clear glass. The beam is then reflected upon the screen, where you observe

Digitized by Google

a bright circular patch of light which has passed through the hole in the coil. On pouring into the tube a little of the magnetic mud the light entirely disappears: the liquid is absolutely opaque. But now observe the effect of magnetizing the liquid. An electric current is switched on, and circulates in the wire coil around the tube. Light appears, not suddenly, but with a certain amount of deliberation, as the minute magnetic particles turn round and orient themselves along the axis of the tube, and arrange themselves in lines. On switching off the current these lines break up, the opaque particles in the liquid again assuming miscellaneous positions, and the light is again obstructed. Each time the magnetizing current is turned on the light reappears, again to disappear when the current stops.

After these experiments one need not labour the argument that during the growth of the magnetism of a magnet there occurs a physical arrangement or rearrangement of its parts. If it be conceded that the small parts, whether molar or molecular, are initially themselves magnets, then the act of magnetization requires and implies no more than a change in the configuration of those parts. So far as material magnets are concerned, and it is to such that Weber's and Ewing's theories alike apply, this proximate account of the growth of magnetism is complete. But when we pass to the magnetism of the medium, whether of the ether, or of the air, or other matter of the kind commonly called non-magnetic, the explanation that is so satisfactory in the case of the magnetizable bodies wholly fails. Here there is nothing at all of the same sort. The phenomena of magneto-optics, which are far remote from the immediate subject in hand, suggest

Digitized by Google

something totally different, something in the nature not of a statical alignment of particles but of rotation around the same axes along which the magnetic particles, if such were present, would orient themselves. But such rotation must necessarily be a rotation of the ether, not of the molecules of the substance, whether air or other. Faraday's conception of the physical lines of magnetic force passing through space from magnet to magnet, or from pole to pole, and forming physical continuations of the material lines of magnetic structure within the magnet, is here also most suggestive, most fruitful. Grant that there are or may be in the ether such vortices having definite axial directions around which they whirl, then the alignment of magnetic particles in the act of magnetization implies that the particles of iron are possessed of some physical property by reason of which they tend to set themselves along the axis of such a vortex or at least parallel to that axis. In this view Ampère's hypothesis that all magnetism might consist in the circulation of electric currents within the magnet is most suggestive. One must make the theory more precise by postulating first that these Ampèrean currents circulate around each molecule separately, and secondly that they are perpetual. If perpetual, then clearly they differ from ordinary electric currents as we know them in matter, in that they waste no energy, that they meet with no resistance. If resistance be only met with where electricity passes from one molecule to another, and not where electricity simply circulates within or around the molecule, the perpetuity of the currents violates no physical principle. Into the deep question whether in these molecular circulations the *ions* or *electrons* are

Digitized by Google

the essential agents we cannot here enter. Observe only that on any such explanation we have to admit that the molecules of the three metals iron, cobalt, and nickel have from their creation been endowed with this sort of perpetual circulation, by virtue of which they and they alone can possess the property of sensible magnetism.

At the outset of this lecture I divided the methods of magnetizing into the new and the old, and it remains to consider how in each case the magnetism grows. Here we derive the greatest assistance by using Faraday's conception of physical lines of force. In the act of bringing a magnet into contact with a piece of iron or steel for the purpose of magnetizing the latter, we subject the material to the influence of the magnetic lines of force which extend out from the poles of the magnet. The molecules of iron or steel turn toward alignment with those lines exactly as before explained.

But in the case of magnetization by the circulation of current the matter is not so obvious. Both in the case of the tube containing iron filings and in that of the experiment with the magnetic mud, we have seen the surprising fact that the circulation of electric current round outside the tube has the effect of causing the magnetic particles within to turn so as to point along the axis. I referred to this phenomenon of magnetizing by means of an outside circulation of current as a marvel; and a never ceasing marvel it is to me. It is quite as miraculous as that the walls of Jericho should fall down as the result of an army marching round outside. A nearer parallel would be this: that as the result of an army of electrons circulating round outside the walls of Jericho every iron

Digitized by Google

rod, every iron nail, every iron poker inside the walls of Jericho should forthwith rise up and stand on end. That is exactly what on a minute scale actually occurred when the electric current circulated round the outside of the glass tube containing the magnetic particles. But how did this mysterious action come about? How did the effect, which obviously originated in the coil of copper wire, cross the intervening walls of glass and reach the interior particles? Clearly there is here involved some physical process needing to be elucidated. What evidence can experiment afford as to the nature of this process?

Well, here we must revert to those fundamental experiments of Faraday which have been the starting-point of modern electrical theory as well as of modern engineering, in which he first generated electric currents on magnetic and mechanical principles. When Faraday discovered that electric currents could be generated by the mere movement of a magnet in the neighbourhood of a coil of wire, without friction or even contact of any kind between the two, he was compelled to think ahead and speculate on the physical nature of the operation. To him, as to Newton, the idea of action at a distance appeared essentially unthinkable. But he perceived a way out of the intellectual absurdity in the existence of those invisible magnetic lines which surround the magnet and constitute a sort of atmosphere in the neighbouring space. To this atmosphere, which extends visibly outward from the poles of the magnet, he gave the name magnetic *field*[1]; and he was led to attribute to the magnetic lines

[1] The term occurs first in Faraday's *Experimental Researches*, Series xx (1845), Vol. III, p. 30 of the Reprint of 1855.

Digitized by Google

which filled this field certain physical properties of their own. He found, in fact, by comparing the patterns of the lines, as mapped out by the process of sprinkling iron filings, with the electrical inductive effects which could be obtained in the field, that there was an intimate relation between the two. If a wire loop (united to a sensitive galvanometer to detect any electric currents that might be generated in it) was moved about in the field, currents were generated only if the wire loop cut across the magnetic lines. Moving the loop so as to slide *along* the invisible lines generated no current. Moving the loop so as to enclose more of the magnetic lines generated currents; while moving the loop so as to enclose fewer lines generated currents that flowed in the opposite sense around the circuit. These lines must therefore, though invisible, have a physical existence. They formed, as it were, prolongations, reaching out into space, of the structure of the magnet itself. But as they existed quite independently of the question whether the space was occupied by air, or vacuum, or any non-magnetic material, they clearly constituted an immaterial phenomenon. Their presence indicated, as we should now say, some physical phenomenon of the ether. Faraday further showed that they were correlated to other known magnetic phenomena. In every case where two poles attracted one another, an examination of the field showed that the magnetic lines of the field formed continuous curves stretching from one pole to the other. In every case where two poles repelled one the other, examination showed that though each pole possessed its own system of radiating lines they did not coalesce, but turned away from one another as if obeying some

Digitized by Google

invisible mutual repugnance. Hence he was led to formulate the rule that the magnetic lines behaved as though there were a tension along them causing them to tend to straighten themselves, and as though they exercised also lateral pressures tending to push them sideways away from one another. I have but to throw upon the screen photographs of the filing-figures made between (*a*) two attracting poles and (*b*) two repelling poles for you to realize the conception. It sorely puzzled the metaphysicians and mathematicians of that day. Steeped in the accepted notions of action at a distance, of which a fundamental proposition was that any force acting between two points *A* and *B* must act in the straight line between them, they regarded Faraday's curved lines of force as an unscientific paradox. Still less willing were they to admit that to these curved lines of force—mere abstractions as they deemed them—there could be attributed any such physical properties. When later Clerk Maxwell translated Faraday's work into the language of mathematical physics, and demonstrated that there must exist a tension along and a pressure across the lines of every magnetic field, the essential accuracy of Faraday's mode of regarding the subject was triumphantly vindicated. The ether-stresses, or stresses in the surrounding medium, are not a mere accompaniment of the magnetic attractions and repulsions, they are their actual cause. In reality the north pole of one magnet does not 'attract' the south pole of another magnet. They are pulled together, or urged together by the stresses in the intervening space, stresses of which these lines of iron filings are, when obtained, an outward and visible sign.

Digitized by Google

To these ideas Faraday joined yet one other, namely, the notion of permeability of a medium toward these magnetic lines. He regarded iron as a substance which conducted them readily, while air was a less good conductor of them. And he himself discovered the class of diamagnetic bodies, of which bismuth is the type, which are of lower permeability[1] than air or ether. More important still in the present matter, Faraday investigated the magnetic properties of the copper wire while it is in the act of conducting an electric current. He found that the wire is also surrounded by a magnetic field—a field belonging not to the copper but to the electric current it conducts—which appears in the space around the wire when the current is turned on, and disappears when the current is turned off. This field differs in its disposition from that of any ordinary magnet. For, while the magnetic lines in the fields of magnets are disposed in tufts which emanate from the poles, forming, as just remarked, continuations of the internal magnetic structure; those of the electric conducting wire are disposed in concentric circles around the wire, each closed on itself. The magnetic forces in the field of the conducting wire are *lateral*, as is evidenced by the deflexion of the compass-needle which tends to set itself *across* the conducting wire. Here again is evidence that the actions produced by the so-called electric current upon compass-needles or other objects not in contact with it, and which are in one sense actions at a distance, are also in reality actions in an intervening medium. When an electric current (so called) is turned on, and grows, this surrounding magnetic field also grows. In

[1] The term *permeability* is more recent. It is due to Lord Kelvin in 1872; see *Papers on Electrostatics and Magnetism*, p. 484.

Digitized by Google

other words, there is set up during the period of growth a system of concentric stresses in the surrounding medium, which spread all around and may thus reach bodies at a distance away. We may indeed begin to understand that the operation called by us starting an electric current consists in reality in setting up this system of stresses in the medium surrounding the wire. Indeed Poynting has deduced from Maxwell's equations that the energy which maintains the current in flowing through the resistance of any part of a circuit—for instance in an interposed bit of thin wire which is thereby heated—travels to that part not, as was formerly supposed, along the inside of the wire, but follows a path through the surrounding medium and enters the wire laterally. I have drawn attention to this phenomenon of the growth of the electric current, for we must presently consider it further.

I will merely remark in passing that whenever we turn on any electric current, that current will take time to attain its full strength; the time taken depending on conditions which may determine it to be a minute fraction of a second, or may prolong it for several minutes. I will also remark in passing that if the essential part of an electric current be this whirl of magnetic lines surrounding the conductor, it becomes intelligible that it should be possible to generate or induce an electric current in a loop of wire by moving it mechanically across the magnetic field of a magnet, or by plunging a magnet into a coil of wire.

Let us pursue further the singular lateral or transverse relations which have already been noted. To magnetize a bar of iron, or to make iron filings in a tube align themselves longitudinally, we have to surround

Digitized by Google

the bar of iron or the tube of filings with a coil of wire and cause the electric current to circulate laterally around the rod or tube. I put the question a while ago in the case of the filings inside the glass tube:—How did the effect, which obviously originated in the coil of copper wire, cross the intervening walls of glass and reach the interior particles? Clearly we are now in a position to answer at least thus far, that when the current was turned on and grew there grew up surrounding every bit of the copper coil a system of invisible magnetic lines, which spread thence and conspired to form a magnetic field for the whole coil, which magnetic field extended into the glass tube and tended to produce alignments at right angles to the direction in which the copper wires lay: and as the copper wires lie transverse to the axis of the tube their magnetic effect will therefore be along that axis.

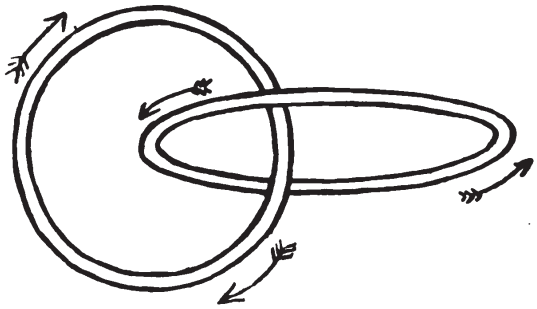

FIG. 3.

Faraday drew attention to this relation by a picture representing two rings interlinked with one another, their planes being mutually at right angles to one another. One represents the electric circuit (of copper), the other the magnetic circuit (of iron) interlinked with it. Consider what would occur if we could cause an electric current to grow in the copper ring. It would become surrounded with magnetic lines invisibly encircling it, which, beginning at the surface of the copper, would enlarge themselves and spread outward (as the wavelets do from the centre of disturbance on the

Digitized by Google

surface of a pond when a stone is thrown in). Then, since iron is a better conductor for magnetic lines than air is, they would, as they enlarge, enter the iron ring and bury themselves in it, conferring on it a magnetic structure. The ring in fact would become magnetized. Now mark this. Such a ring would have no poles. The lines of magnetic structure would each be re-entrant on itself. When the current was switched off the lines would collapse back into the copper ring and disappear. Some might be left behind in the iron ring representing a residual magnetization. Now in this process it is clear that the magnetic lines would enter and leave the iron ring laterally, flank-wise. They would not enter endways, for each magnetic line is itself a closed curve, and has no ends. To put it in other words, when iron (whether a ring, a rod, or any other form) is magnetized by the penetration into it of the magnetic lines of some externally-produced magnetic field, these lines do not enter it longitudinally, like needles thrust into a pincushion, but enter it laterally. In fact this is always so. *The propagation of magnetism is always and in all cases lateral.*

Faraday himself drew attention to the circumstance that the magnetic lines always form closed curves. To him we owe the conception of the magnetic circuit. We may think indeed of a bar magnet as having ends—material ends—which we call poles, where the magnetic lines pass out of the iron into the air or re-enter the iron from the air; but the lines themselves are always re-entrant. The more completely the iron is shaped into a re-entrant form, the better adapted is it to act magnetically; and so it comes about that being now, thanks to Maxwell, to Rowland, to Bosanquet, to Kapp, and to

Digitized by Google

Hopkinson, able to calculate the proportions of magnetic circuits, we can produce magnets which, for their size, are enormously more powerful than anything hitherto possible.

Look for example at this little electromagnet[1]. It weighs with its keeper only three and a half pounds; and the copper wire coil—a simple ring of about eighty turns—which drops into an annular groove in its face weighs only six ounces. But, energizing it by means of a battery of four cells, it is able, as you see, to hold up no less than 300 pounds. Returning to Faraday's researches on the induction of currents by the mechanical movement of a coil of wire across the lines of a magnetic field, let me show you the fundamental experiment by means of a very simple apparatus, the facsimile of one of Faraday's own. Upon the table stands a strong horse-shoe steel magnet with its poles upward. The magnetic lines which leave the steel at the north pole re-enter it at the south pole. They cross the intervening space invisibly in arched curves, the field being most intense in the gap—about an inch wide—between the upper ends of the two limbs. Across the top of these limbs there is now placed a rod of iron with a handle at each end. Around the girth of this rod there has been constructed a bobbin or coil of insulated

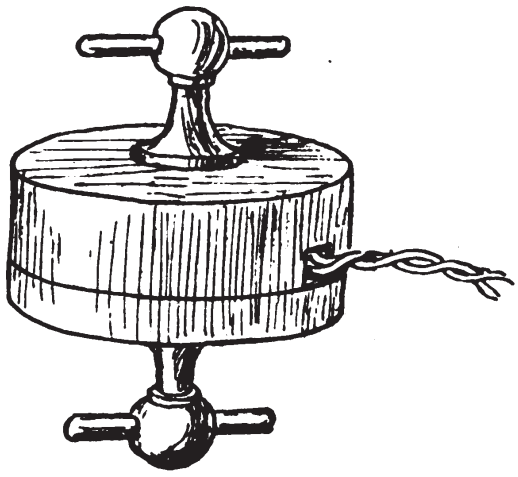

FIG. 4.

[1] It was constructed for me by my assistant Mr. Dennis Coales, B.Sc.

Digitized by Google

copper wire, consisting of about three hundred turns. The lower part of this coil lies in the gap between the magnet limbs. What will occur if the coil be suddenly lifted from the magnet? Every turn of the wire will cut across those magnetic lines and in so doing there will be generated a current in the coil. To make that current visible, Faraday resorted to the very simple device of attaching the ends of the wire to two springy pieces of brass which touched lightly against one another. When the coil is suddenly lifted, by putting one's hands below the handles and jerking them upward, the shock causes the brass contact-points to chatter, and at the chattering contact you will perceive a small bright spark[1], even though the room be not darkened. Faraday used a very similar device, a photograph of which is shown, in 1835 on the occasion of the visit to Oxford of the British Association, to draw a spark by induction from that celebrated globular loadstone which stands in the Museum of the University; an experiment which excited at that date the most intense interest. The device

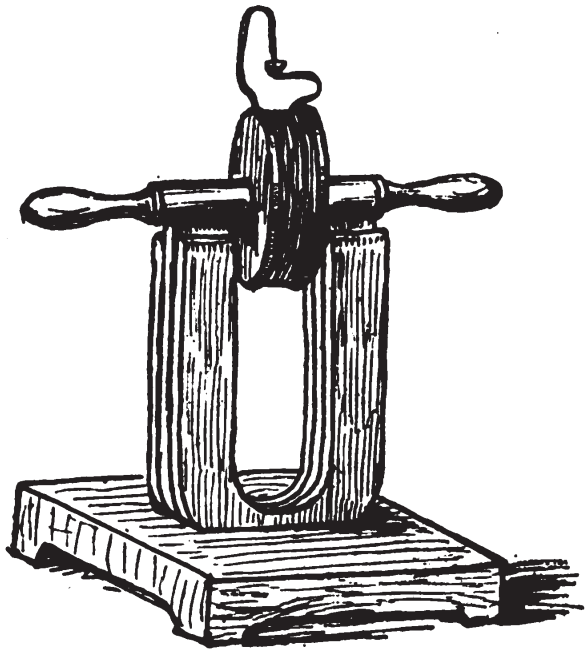

FIG. 5.

[1] To enhance the brightness of the spark the surface of the brass should be freshly amalgamated with quicksilver.

Digitized by Google

was a simple home-made bit of apparatus consisting of a coil of insulated wire, with a chattering contact, wound upon one end of a piece of iron pipe.

To complete this brief survey of these fundamental experiments I must refer to Faraday's celebrated ring, by means of which, indeed, he first made the discovery of induction. The ring was of iron, about 8 inches in diameter. Upon it he wound two separate coils *A* and *B*, surrounding its opposite halves. He found that whenever a current was started or stopped in coil *A* a momentary current was generated in coil *B*. Now consider this process, involving a doubly lateral action. The current (from a battery) sent into coil *A* magnetizes the ring: but not by pushing magnetic lines longitudinally into the iron. It sets up closed magnetic curves which enlarge and spread laterally. In so doing—see the dotted line in Fig. 6—they must needs cut across the wires of coil *B*, and in so cutting across them generate new electric currents in that coil. So at the turning on of the current in *A*, during the growth of the magnetism in the iron ring there will be an induction current in *B*; and, on turning off the current in *A*, while the magnetism of the ring is dying down and the magnetic lines are

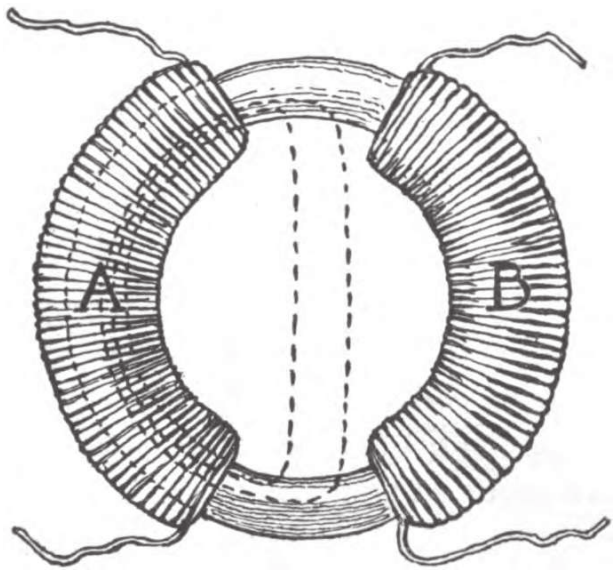

FIG. 6.

Digitized by Google

collapsing back, there will be an inverse induced current in *B*. If we could turn the current on and off very rapidly—say 200 or 300 times a second—these inductive effects would be much enhanced. This I can do by the aid of an electrolytic interruptor. This is in fact a modified form of Wehnelt's break which Mr. Dennis Coales constructed for me. This interrupted current being supplied to a coil of wire which surrounds an iron core, the magnetism is caused to grow and to disappear with corresponding rapidity. This magnet produces under these circumstances many extraordinary phenomena. I can light up a little glow lamp by attaching it to a second coil that is itself merely held over the top of the iron magnet. The transformations of energy and its transference from one coil to the other, and so to the lamp, are precisely of the same sort as was the case in the transmission of energy from coil *A* to coil *B* of Faraday's ring. Still more curious is the mechanical effect[1] produced upon a single ring of metal, in fact an aluminium ring, placed over the iron magnet core; it is mechanically repelled by the reaction of the currents induced within it, and flies up into the air. If forcibly held down it grows hot. If the ring be painted with that heat-indicating paint[2] which turns red as the temperature rises, the fact that it is heated by these internally-induced currents is made visible to the eye.

In the endeavour to emphasize by illustration this salient fact in the growth of magnetism that the propagation of the magnetic forces is always lateral, it has occurred to me to avail myself of the optical aid of the animatograph. The pictures to be shown are mere

[1] First described by Prof. Elihu Thomson, of Lynn.

[2] The double iodide of mercury and silver.

Digitized by Google

diagrams photographed upon the kinematographic films[1]. The first of these is very simple. It represents the growth of the magnetic field surrounding a simple straight conductor of wire carrying a current. The conductor is viewed in section simply as a central circular spot. The field consists of concentric circles which appear at the centre and enlarge, like the ripples on a pond. The current is represented as growing to a maximum, remaining stationary for an instant, and then dying away. In fact the moving picture represents, when repeated, the magnetic field surrounding an alternating current in a straight conductor.

The second of the kinematographic pictures represents a portion of the revolving armature of a dynamo-machine, in order to show how the magnetic lines shift from one projecting iron tooth to another during the rotation of the armature.

A third illustrates the way in which

[1] They were photographed by Mr. R. W. Paul, inventor of the animatograph, from a series of drawings prepared by myself and Mr. Dennis Coales, B.Sc. Some of the series required no fewer than 50 or 60 separate pictures to be drawn on cards to give the consecutive series of positions, which by the Paul animatograph were recombined into moving pictures.

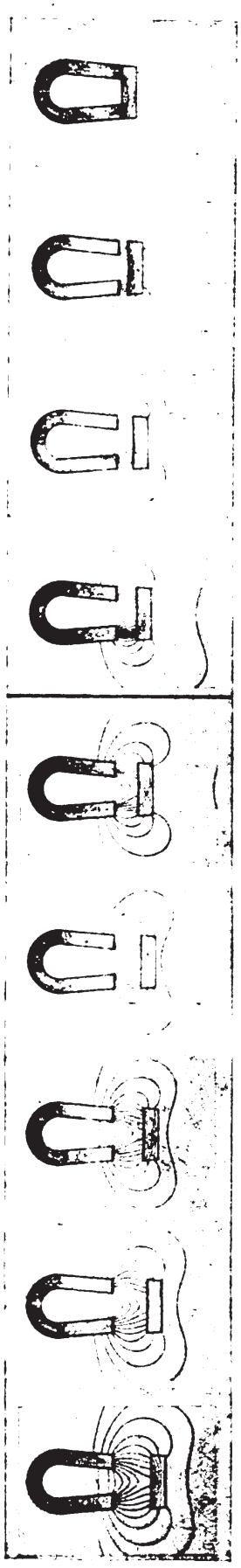

FIG. 7.

Digitized by Google

the iron keeper of a horse-shoe magnet is magnetized by the magnet during its approach toward the poles. A portion of the series of separate pictures is reproduced in Fig. 7. Incidentally the pictures illustrate several other things. They illustrate a point remarked by Faraday, that on placing the keeper upon the poles of the magnet the magnetic field, in the neighbourhood of the magnet right and left, is weakened. At first the magnet is shown without its keeper, with all its own magnetic lines curving round, each line being a closed or re-entrant curve which passes round the bned of the horse-shoe. Then the iron armature comes into view. Some of the magnet's lines spread out towards it and enter it, penetrating the iron freely. Each successive magnetic line enters sideways. They concentrate themselves in the iron, and draw it toward the magnet. As it comes nearer and nearer, the outside space is robbed of all the magnetic influences, until, when the keeper makes contact across the poles, the whole of the magnet's lines pass through it, the magnetic circuit being completed through iron. Then comes a hand and pulls off the keeper; and as it recedes from view we watch the re-emergence of the magnetic field and its return to the primitive condition.

A last series of kinematic pictures is a diagrammatic representation of the magnetization of an iron bar by means of a surrounding copper wire of four turns only. The diagram was prepared from an actual filing-pattern, which served as a guide in drawing the forms of the magnetic curves. At first we see merely a straight bar and the outlines of the sections of the wires. Then the current begins, and as it grows it creates magnetic

Digitized by Google

lines, at first in closed curves around the copper wires, as in the first of the pictures. But these curves as they enlarge coalesce and extend both outwards and inwards. Inwardly they spread into the iron bar, entering it laterally, and extending through it from end to end, to be followed by others which come crowding in until the current and the magnetization have reached their maximum. Then the picture reverses the operation, and shows the magnetization dying away. The lines leave the iron core as they entered, laterally, and collapse one by one back into the coil and so disappear.

In the endeavour to ascertain the nature of the processes which occur both within the magnet and without it during the growth of the magnetism we have come face to face with many points which suggest lines of thought.

The magnetism of a magnet we have seen to be a property of the metal iron, intimately connected with the arrangement of its particles, involving a kind of structure, and its introduction accompanied, as Robert Boyle remarked, by the production of mechanical changes in them. But we have also seen that it is a property of the ether of space, and that the lines of structure within are prolonged into, or are themselves mere prolongations of, invisible lines of some more recondite structure of the external medium.

We have seen that the electric current, so called, manifests lateral magnetic forces, and that it is not unreasonable to hold that the essential thing in what is called an electric current *in* a wire is in reality the system of magnetic whirls which are found surrounding

Digitized by Google

it in the ether; the wire acting as a sort of guiding core for these whirls.

We have seen that the propagation of the magnetic forces is lateral: that the magnetic lines always move sideways and do not penetrate endways. We have reason to think that the energy-flow, in cases where energy is transmitted electromagnetically, takes place laterally, never along the magnetic lines, but across them. Without pushing speculation too far, does not this suggest that in the case of other natural forces also the propagation of them, which may at first sight seem to be longitudinal—in the line of action,—is in reality lateral? Perhaps cohesion, perhaps gravitation itself, may be propagated across space by forces which operate laterally: who can yet say?

Permit me then to conclude this discourse of the occult virtues of the magnet with one single thought more. Amongst the still hidden secrets of nature there is one that has as yet defied the wit of man to discover. Ever since the days of Gilbert it has been known and admitted that the earth is a great magnet. But it was not always a magnet. Our knowledge that all magnetic substances lose their magnetism at full incandescence is convincing that when this globe was in the heat of its cosmic evolution, and before it had cooled down enough to be habitable, it was not a magnet. How, then, has its magnetism grown to be what it is? Is its magnetism still growing? By what process did it grow? Not by the old process of rubbing with another loadstone. Not by the new process of encircling it with a magnetizing girdle of copper wire. By what process then? It is evident that there must be some other process, some method yet undiscovered; or if not undiscovered, yet

Digitized by Google

unrecognized as the cause. But such thoughts as I have upon this yet unrecognized way I must reserve for some other opportunity. There is ample room for speculation. Our study of the growth of magnetism must not tempt us too far. It has led us a long way from the mechanical changes and occult virtues which were the admiration and the study of Robert Boyle.

THE LIBRARY OF THE
JUN 2 - 1939
UNIVERSITY OF ILLINOIS

Digitized by Google

Digitized by Google